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RAPID, EFFICIENT CHARGING OF LEAD-ACID AND NICKEL-ZINC TRACTION CELLS

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ABSTRACT

Lead-acid and nickel-zinc traction cells were rapidly and efficiently charged using a high rate tapered direct current (HRTDC) charge method which could possibly be used for on-the-road service recharge of electric vehicles. The HRTDC method takes advantage of initial high cell charge acceptance and uses cell gassing rate and temperature as an indicator of charging efficiency. On the average, in these preliminary tests, 300 amp-hour nickel-zinc traction cells were given a HRTDC (initial current 500 amps, final current 100 amps) to 78 percent of rated amp-hour capacity within 53 minutes at an amp-hour efficiency of 92 percent and an energy efficiency of 52 percent. Three hundred amp-hour lead-acid traction cells were charged to 69 percent of rated amp-hour capacity within 46 minutes at an amp-hour efficiency of 91 percent with an energy efficiency of 64 percent. In order to find ways to further decrease the recharge times, the effect of periodically (0 to 400 Hz) pulse discharging cells during a constant current charging process (94% duty cycle) was investigated. Preliminary data indicate no significant effect of this type of pulse discharging during charge on charge acceptance of lead-acid or nickel-zinc cells.

LEAD-ACID AND NICKEL-ZINC TRACTION CELLS were rapidly and efficiently charged using a high rate tapered direct current (HRTDC) charge method which could possibly be used for on-the-road service recharge of electric vehicles. The HRTDC charge method takes advantage of initial high cell charge acceptance, and uses cell gassing rate and temperature as an indicator of charging efficiency.

On the average, in these preliminary tests, 300 amp-hour nickel-zinc traction cells were given a HRTDC (initial current 500 amps, final current 100 amps) to 78 percent of rated amp-hour capacity within 53 minutes at an amp-hour efficiency of 92 percent and energy efficiency of 52 percent. Three hundred amp-hour lead-acid traction cells were charged to 69 percent of rated amp-hour capacity within 46 minutes at an amp-hour efficiency of 91 percent with an energy efficiency of 64 percent. In order to find ways to further increase charge acceptance, the effect of periodically (0 to 400 Hz) pulse discharging cells during a constant current charging process (94% duty cycle) was investigated. Preliminary data indicate no significant effect of this type of pulse discharging during

charge on charge acceptance of lead-acid or nickel-zinc cells.

INTRODUCTION

Recently there has been a growing interest in electric vehicles as a viable mode of urban transportation. This interest has been precipitated by a shortage of domestic oil, and by a more pollution conscious society. For an electric vehicle to be successful it must, of course, be accepted by potential users. The range of typical electric vehicles of today with the present generation of lead-acid batteries is less than about 50 miles on a single charge. For most users it is desirable to extend this range. Also in some industrial fleet applications increased vehicle utilization is needed. One method of increasing an electric vehicle's range and utilization may be to rapidly recharge the battery at a suitably equipped on-the-road service station in a similar manner as IC vehicles now refuel with gasoline at a service station.

Various methods of rapidly charging batteries have been proposed and reviewed (1).** In some of the more promising methods the cell gassing rate is used to control charge current (1). Other rapid methods employ pulse charging (2,3).

After reviewing this literature, a high rate tapered direct current (HRTDC) method was selected for preliminary tests on 300 amp-hour lead-acid and 300 amp-hour nickel-zinc traction cells. This method takes advantage of the initial high cell charge acceptance, and uses the cell gassing rate as an indicator of how efficiently charge is being accepted.

In addition, because of conflicting reports concerning the benefits of pulse charging to charge acceptance (2,3) on the one hand and lack of demonstrable benefit on the other (1,4), a few exploratory tests of pulse charging were also run.

In this paper the HRTDC method of rapid efficient charging is described, the results of HRTDC charging of 300 amp-hour lead-acid and 300 amp-hour nickel-zinc traction cells are presented and the preliminary results of a limited study of pulse charging on charge acceptance are discussed.

EXPERIMENTAL

CELL CHARGER - The cell charger used is versa-

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**Numbers in parentheses designate References at end of paper.

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tile and allows for operation in either the direct current or pulse current mode (5). A wide range of adjustments of charge current, discharge current and pulse timing in either direct current or pulse current mode is available.

The charger has the following characteristics:

1. A charge (positive) current from 0 to 1000 amps.
2. A discharge (negative) current from 0 to 1000 amps.
3. Charge and discharge current pulses from 0 to 1000 Hertz.
4. Continuously variable discharge time from 0.1 to 100 milliseconds.
5. Provides zero cell current (zero charge and discharge current) controlled by an electronic signal.
6. Operates in either continuous charge or continuous discharge mode.

The current switching is done with a water cooled high current transistor switch. The transistor switch is capable of carrying 1000 amps dc as well as switching 1000 amps at a 1000 Hz rate. Water cooling is provided for all of the solid state power components in order to obtain the compact, low parasitic inductance configuration necessary for high rate, high current switching.

MEASUREMENTS AND PROCEDURES

During each high rate tapered direct current charge experiment the quantities measured and their accuracies were as follows: Cell temperature ($\pm 1^\circ\text{C}$ limit or error); cell gassing rate ($\pm 0.5\%$), in some cases evolved gases were analyzed to obtain reliable gassing rates; amp-hours ($\pm 0.5\%$); cell voltage ($\pm 0.5\%$); and charge current ($\pm 0.3\%$).

Cell temperatures were measured using an iron-constantan thermocouple located in the cell electrolyte. The thermocouple was coated with epoxy to prevent attack by the electrolyte.

Cell gassing rates were measured during charge using a calibrated laminar flowmeter (0 to 300 cm^3/min at 21°C , 760 mm of Hg). Since the flow rate depends on gas temperature, the cell gas was heated to a constant 65°C via a heat exchanger prior to entering the flowmeter. Flow rates were then reduced mathematically to standard conditions, i.e., 21°C and 760 mm of Hg. Since the gas flow rate also depends on composition, gas samples were taken periodically and analyzed by gas chromatographic analysis. The gas evolved by the lead-acid cell was about 67% H_2 and 33% O_2 by volume. The gas evolved by the nickel-zinc cell was about 10% H_2 and 90% O_2 by volume.

Cell charge and discharge amp-hours were measured using a conventional amp-hour meter. Cell voltage as a function of time was recorded on a strip chart recorder, and cell current was calculated from voltage measured across a shunt.

Amp-hour efficiency (charge acceptance) was obtained by discharging the cell after charging was completed at various decreasing current levels to a 1.0 volt cutoff in the case of nickel-zinc and a 1.75 volt cutoff for lead-acid. The amp-hours delivered at each current were obtained from the amp-hour integrator and totaled. A typical discharge amp-hour determination and the currents used for these measurements are shown in Tables 1 and 2 for nickel zinc and lead acid, respectively. The

total amp-hours delivered to the cell during charge were obtained in a similar manner. Amp-hour efficiency was calculated as a ratio of total amp-hours out of a cell during discharge to the total amp-hours into the cell during charge. The energy efficiency was calculated as a ratio of total energy out of a cell during discharge to total energy into the cell during charge. Total energy out of, or into a cell was calculated by summing the product of measured amp-hours and average cell voltage at each current level. Average cell voltage was obtained from a strip chart recording of cell voltage as a function of time.

Experiments were conducted to define the best combination of charging rate, temperature rise and gassing rate to obtain a reasonable charge acceptance in the shortest time. An initial 500 amp charge was tapered in 50 amp increments to 100 amps while gassing rate and temperature were monitored and held within preset limits chosen as experimental parameters. Efficient charging required that the gassing rate be less than 10 to 20 percent of the rate equivalent to the charging current and a rate of temperature increase of about 1.2°C (2.2°F) per minute.

The pulse charge experiments were limited to a periodic pulse discharge during a constant current charge at 250 amps. The discharge pulse was also set at 250 amps but the frequency was varied from constant current (zero Hz) to 400 Hz with a constant 94 percent duty cycle. During the charge, cell pressure and temperature were monitored and the charge was terminated when the cell pressure reached 3.5×10^4 newtons/meter² (5 psi). The charging current as a function of time with the discharge pulse are shown schematically in Figs. 4 and 5.

The 250 amp current was chosen to reduce the possibility of "aging effects" associated with the cycling excursion during the duration of the tests masking the influence of pulse frequency on charge acceptance at currents higher than the c rate. The 94 percent duty cycle was selected because it allowed a relatively large charge time and with the charger equipment used preserved a rectangular pulse shape over the 1 to 400 Hz frequency range. The 3.5×10^4 newtons/meter² (5 psi) pressure cutoff was dictated by the cell case construction.

RESULTS AND DISCUSSION

HIGH RATE TAPERED DIRECT CURRENT CHARGING - In Fig. 1 the charge current, cell temperature, and gassing rate as a function of charge time, for a representative 300 amp-hour nickel-zinc cell is shown. The initial charge current was 500 amps and was tapered to a final value of 100 amps in 50 amp increments. During the initial portion of the charge the gassing rate was low, however, the rate of cell temperature increase was rapid ($\sim 1.2^\circ\text{C}/\text{min}$ ($2.2^\circ\text{F}/\text{min}$)). Because charge acceptance of the nickel electrode is greatly effected by temperature (6), the charge current was gradually stepped down. At a charge current of about 350 amps the current was decreased further due to onset of gassing. Onset of gassing for efficient charging was defined as the point where the gassing rate rises steeply, to about 10 to 20 percent of the rate equivalent to the charging current. Some gas is evolved at low rates prior to this point. For instance, at the end of the 350 amp charge the gassing rate was about

125 cm³/min (STD conditions 21° C, 760 mm of Hg), which corresponds to about 10 percent of the charging current producing gas (90% calculated amp-hr efficiency).

A typical charge input as a percentage of rated capacity as a function of charge time is shown in Figs. 2 and 3, and results for each experiment are summarized in Tables 3 and 4 for nickel-zinc and lead-acid cells, respectively. For nickel zinc on the average about 78 percent of rated 300 amp-hour capacity can be returned within 53 minutes at an amp-hour efficiency of about 92 percent and an energy efficiency of 52 percent. For lead-acid on the average about 69 percent can be returned within 46 minutes at an amp-hour efficiency of about 91 percent and an energy efficiency of 64 percent. The use of this charging method does provide a way of charging nickel-zinc and lead-acid traction cells in times short enough to be of potential interest in an on-the-road service station context.

The effect of the HRTDC method of charging on cell charge/discharge cycle life is unknown at this time. However, since during the charging process the gassing rate and cell temperature are controlled, it is reasonable to expect that this rapid method of charging would not be as detrimental to battery cycle life as other high rate methods, which are believed to produce excessive gassing rates and high cell temperatures.

PULSE DISCHARGE DURING CHARGE - Figure 4 shows for a 300 amp-hour nickel-zinc traction cell the percentage charge input as a function of a 94 percent duty cycle charge/discharge current pulse for frequencies ranging from zero to 400 Hertz. No significant effect of pulse charging on cell charge acceptance is evident for these conditions compared with dc charging (zero frequency). In Fig. 5 similar uninteresting results for the same pulse current conditions for a 300 amp-hour lead-acid traction cell are illustrated.

The effect on charge acceptance of further variations of charge/discharge current duty cycle and frequency parameters have not yet been studied but will be the subject of a continuing effort.

CONCLUDING REMARKS

A high rate tapered direct current method controlled by gassing rate and cell temperature appears feasible for charging lead-acid and nickel-zinc traction cells. Preliminary data indicate that periodically pulse discharging during a constant current charging process did not improve the charge acceptance of lead-acid or nickel-zinc traction cells.

The nickel-zinc and lead-acid traction cells used in this work were not specifically designed for rapid charging. Any serious attempt to use and depend upon rapid charging of cells should be reflected in the basic cell design (3). In this respect low cell resistance and optimization for charge acceptance are among the most important features.

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Table 1 - Ampere Hour Determination of a Representative 300 Ampere-Hour Nickel-Zinc Traction Cell

Discharge Current (Amps)	Amp-Hrs Out	Voltage* (Volts)
250	191.5	1.00
150	9.2	1.00
100	5.5	1.00
50	7.6	1.00

Total 213.9

* Voltage at which discharge was terminated.

Table 2 - Ampere Hour Determination of a Representative 300 Ampere-Hour Lead-Acid Traction Cell

Discharge Current (Amps)	Amp-Hrs Out	Voltage* (Volts)
100	163.8	1.75
75	17.6	1.75
50	22.8	1.75

Total 204.2

* Voltage at which discharge was terminated.

Table 3 - Results of Rapid Charging of 300 Ampere-Hour Nickel-Zinc Traction Cells

Cell	Amp-Hrs in	Amp-Hrs out	Amp-Hr Efficiency	Energy Efficiency	Percentage* Charged	Charge Time (min)
106	245	226	92	52	82	59
105	241	214	89	50	80	52
104	227	202	89	51	76	53
110	222	213	96	55	74	49

* Percentage of rated amp-hr capacity (300 amp-hr).

Table 4 - Results of Rapid Charging of 300 Ampere-Hour Lead-Acid Traction Cells

Cell	Amp-Hrs in	Amp-Hrs out	Amp-Hr Efficiency	Energy Efficiency	Percentage* Charged	Charge Time (min)
2	218	204	94	66	73	48
3	204	188	92	65	68	43
4	200	175	86	61	67	46

* Percentage of rated amp-hr capacity (300 amp-hr).

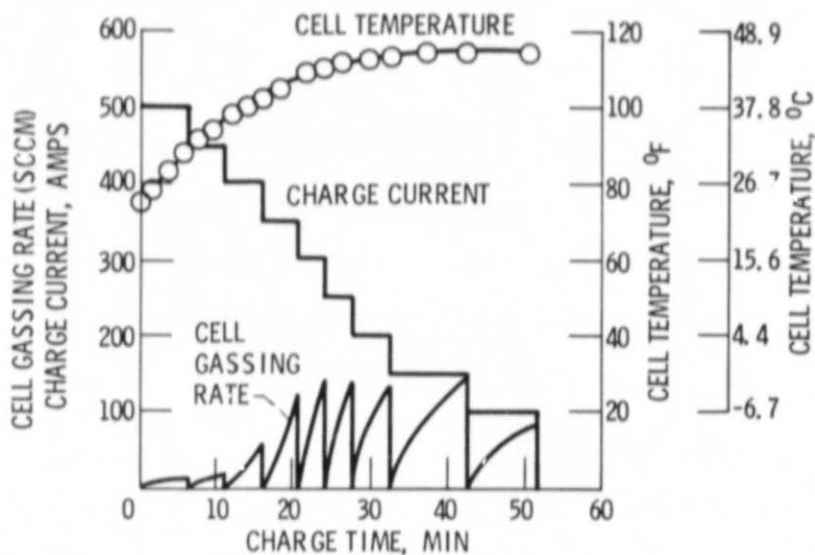


Figure 1. - Charge current, cell temperature, and cell gassing rate as a function of charge time; 300 Ah nickel-zinc cell.

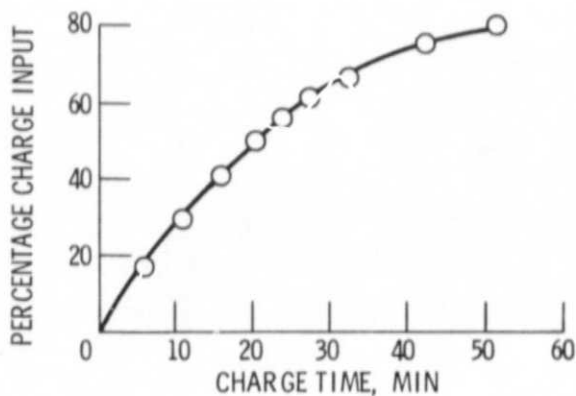


Figure 2. - Percentage charged as a function of charge time for a representative 300 Ah nickel-zinc traction cell.

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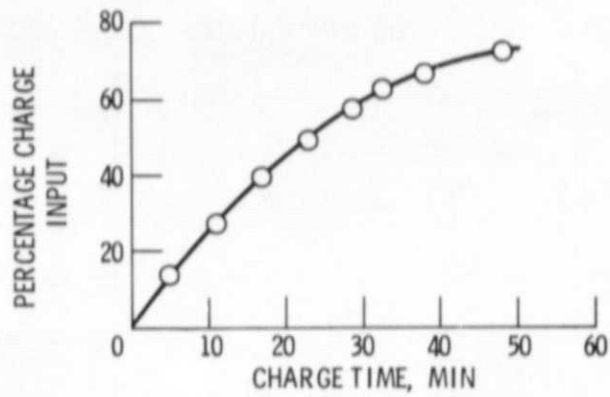


Figure 3. - Percentage charged as a function of charge time for a representative 300 Ah lead-acid traction cell.

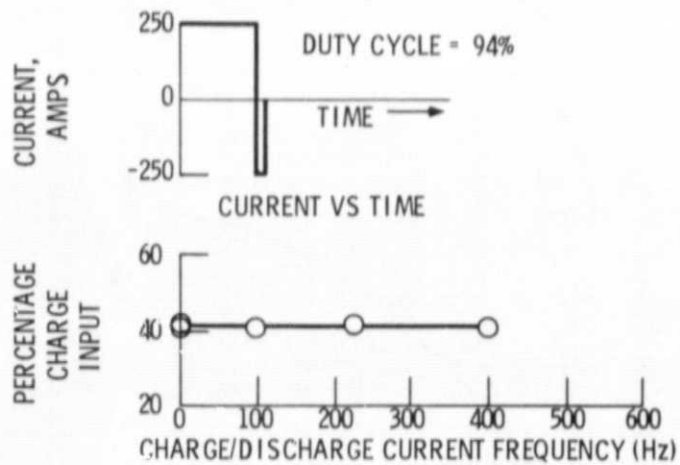


Figure 4. - Pulse charging - percentage charged as a function of frequency for a representative 300 Ah nickel-zinc traction cell.

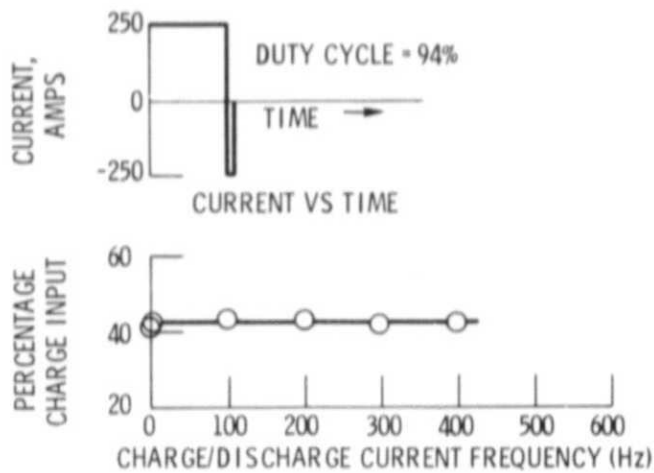


Figure 5. - Pulse charging - percentage charged as a function of frequency for a representative 300 Ah lead-acid traction cell.

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